DETECTION OF SBLOCA IN A STEAM GENERATOR OF A NUCLEAR POWER PLANT

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DETECTION OF SBLOCA IN A STEAM GENERATOR OF A NUCLEAR POWER PLANT

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DEDICATED

TO MY

PARENTS

CERTIFICATE

This is to certify that the work " Detection of SBLOCA in the Steam Generator of a Nuclear Power Plant" by Subhas Chandra Maiti has been carried out under our supervision and has not been submitted elsewhere for a degree.

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ABSTRACT

There are several important causes which can make the nuclear power plant unstable and ultimately lead to an accident . One of such an important causes (faults) is small break loss of coolant accident (SBLOCA) . Slow but steady inventory loss from the steam generator (SG) coolant system will degrade the performance in the long run . It is useful to detect the SBLOCA at proper time . The fault detection can be done in several ways . Out of which General Likelihood Ratio (GLR) test is the most useful one Hitherto , the GLR method has been applied by other researcher only to identify the sensor failures in nuclear power plants .In this work we have attemted to apply the GLR method to detect SBLOCA in the steam generator portion of the primary heat transport system (PHT) . We developed a simplified state space variable model of steam generator and tested the utility of the GLR method . We also developed a simple digital control system to control the outlet pressure of the primary coolant by manipulating the flow rate of the coolant . And level of water is control by manipulating the flow rate of water. The result shows that a leak of magnitude as low as 0.25% of the total flow rate of primary coolant can be detected 90 times out of 100 times within 20.0 seconds (approx) . Thus we can conclude that SBLOCA of the PHT loop can be detected by GLR method . Further study should be done by modelling the complete PHT loop and also the other probable accidents .

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INTRODUCTION

1.1 PROBLEM CONSIDERATION -:

Among the different nuclear power reactors pressurizedheavy water reactors (PHWRs) have few more advantages over others because of it's simplicity in operation and use of natural uranium (0.7 % U-235) as fuel . In India , nuclear plants are mainly based on PHWR; at present four PHWR are in operation . Nuclear power plants (PHWR type) have several units which are inter-connected in a close loop and all PHWR type plants have common primary heat transport (PHT) loop which is shown in the fig 1.1 . Our present problem is to detect leak (only due to small break) in the loop using a model based on statistical method , called GENERAL LIKELIHOOD RATIO (GLR) method

1.2 REVIEW OF THE PAST WORK -:

The GLR method was developed by Willsky & Jones in 1974 . Though i is used to detect faults in many fields , it's application in nuclear field is very few . One such application is fault diagonisis in pressurizer (ref. 14) .Another attempt is made to detect SBLOCA in the heav water reactor (ref. 13) and it is reported that a leak of magnitude 0.25 % can be detected with 98% accuracy .

1.3 THE PRESENT WORK -:

PHT loop contains several units . All the units should be modelled to detect leak in the loop . Only steam generator is considered for present work . In this present work a simplified model is developed for normal operation as well as in the presence of a leak . It is assumed that the plant is operating around a normal steady state and thus the model will not be valid for start-up & shutdown period .

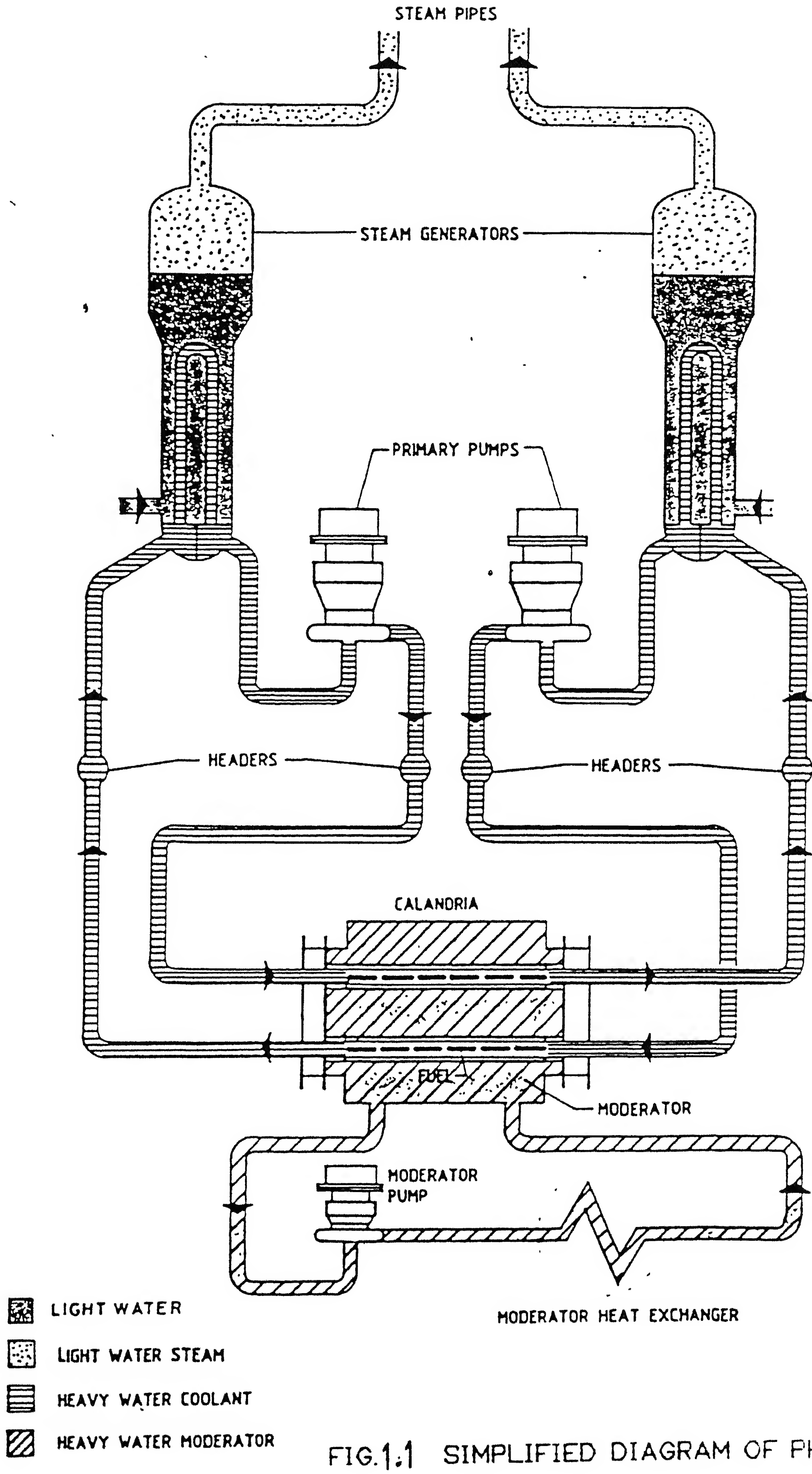


FIG.1.1 SIMPLIFIED DIAGRAM OF PHT LOOP

CHAPTER - 2

THE GLR METHOD

GENERAL LIKELIHOOD RATIO (GLR) is a statistical procedure to detect and identify a fault , if any in the system . It was first introduced by Willsky & Jones (ref. 16) in 1974 . Let us review the method in brief . Further details are available in refer. (16 , 19 , 20 , 21)

2.1 PRINCIPLE OF THE GLR METHOD -:

Let us first consider the GLR method pictorially . Suppose we are given the pattern of differnt measurements with respect to time for different faults . Every fault has specific pattern . This standard pattern can be matched with the plant data obtained and the fault is declared when the trend of data closely matches with the pattern of a particular fault . Fig 2.1 explains this clearly . The fig 2.1a and 2.1b shows the analytically generated pattern for temperature and pressure for two different faults 1 & 2 . In fig 2.1c we plotted schematically the values of the same variables obtained from the plant . This is showing that the pattern generated by the plant data is matching with the analytically generated pattern of fault- 1 .

In the above approach two important questions that need to be answered are ;

(1) HOW TO OBTAIN THE STANDARD PATTERNS FOR DIFFERENT FAULTS

(2) HOW TO MAKE THE DICISION THAT A PARTICULAR FAULT PATTERN BEST FITS THE MEASURED DATA .

The GLR method answers to both the questions , which is stated as follows ;

In order to obtain the standard patterns for different faults

the GLR method needs a linear state space model of the process when the fault is present , that is , a model for every possible faults that needs to be detected in the plant . Based on this model , the GLR method analytically computes the expected pattern of measurement for the fault in a recursive fashion .The mathematics of this recursive computation is described later . These standard patterns for each fault , thus obtained , are stored for subsequent comparision with measured data .

For obtaining the goodness of fit between a standard fault pattern and measured data the GLR method uses a statistical test called LIKELIHOOD RATIO TEST . A statistical test is necessary since we assume both the process model and the measurements are corrupted by random noise due to fluctuation in some of the inputs . The likelihood ratio test can be viewed as a generalization of the standard least square fitting procedure in which the measure ments are weighted inversely according to their variances . The likelihood ratio for any fault is the ratio of two residuals , of the weighted least square fit , the residuals obtained when the measured data is fitted with the pattern for no fault to the residuals obtained when the same measured data is fitted with the standard pattern for the fault . Under the assumtion that all random noise are normaly distributed the likelihood ratio is also equivalent to the ratio of two probabilities , the probability that a fault has occurred to the probability that no fault occured for the given measurements . Thus , if this ratio exceeds a pre specified limit , we can concluded that the fault has occurred . Among different faults , the fault corresponding to the maximum likelihood ratio will be identified as a fault if it's maximum likelihood ratio exceeds the pre-specified limit .

Although we described the procedure in term of measured data , the actual comparision is made using what are called " INNOVATION "

or the difference between measured and predicted values which is described below .

2.2 BRIEF MATHEMATICAL REVIEW OF THE METHOD -:

Let us consider a general state space representation of the modelled equations as follows :

$$\underline{X}_{k+1} = \underline{A} . \underline{X}_{k} + \underline{B} . \underline{U}_{k} + \underline{D} . \underline{W}_{k} \qquad \ldots . \quad 2.1$$

$$\underline{U}_{k} = \underline{C} . \underline{Y}_{k} \qquad \ldots .. \quad 2.2$$

$$\underline{Y}_{k} = \underline{H} . \underline{X}_{k} + \underline{V}_{k} \qquad \ldots .. \quad 2.3$$

where the vectors :

$\underline{X}_{k}$ is deviation of state variables at time k

$\underline{U}_{k}$ is deviation of the manipulated variables

$\underline{W}_{k}$ is deviation of noise at time k

$\underline{V}_{k}$ is of the noise in measurements at time k

$\underline{Y}_k$ is deviation of controlled variables at time k

and matrices :

$\underline{A}$ is the state matrix

$\underline{C}$ is the control matrix

$\underline{H}$ is measurement matrix

$\underline{D}$ is the noise matrix

Now the GLR method can be used in in the following sequence ;

- Kalman filter is used to estimate variables ($\underline{X}_{k+1}$)
- Pattern of innovations are computed
- GLR test is performed to compare with pre-determined patterns
- If fault is present , it's magnitude is declared .

Mathematical description of various steps are as follows :

2.2-A THE KALMAN FILTER -:

The optimal estimate of the state variables and the error covariance matrix are obtained by the use of this filter . The Kalmann filter is basically a least square estimator , and it is minimizing error between the actual plant state vector and the state estimate . Mathematics behind the generation of estimate by Kalmann filter can be described as follows :

Let $\hat{\underline{X}}_{k/k-1}$ is conditional state estimate of the state variables for given measurements upto and including time (k-1) . Corresponding to these estimates the co-varience matrix of the error in these estimate is defined as :

$$\underline{P}_{k/k-1} = \mathrm{cov} \left[\left(\hat{\underline{X}}_{k/k-1} - \underline{X}_{k} \right) / \underline{Y}_{k-1} \right] \quad \ldots\ldots \; 2.4$$

$$\underline{P}_{k/k} = \mathrm{cov} \left[\left(\hat{\underline{X}}_{k/k} - \underline{X}_{k} \right) / \underline{Y}_{k} \right] \quad \ldots\ldots \; 2.5$$

The assumtion of the estimates are given in reference (21) . The computation of the estimates are as follows ;

$$\underline{X}_{k/k} = \underline{X}_{k/k-1} + \underline{K}_{k} \left[\underline{Y}_{k} - \underline{H} \,.\, \underline{X}_{k/k-1} \right] \quad \ldots \; 2.6$$

where ,

$$\underline{X}_{k/k-1} = \underline{A} \,.\, \underline{X}_{k-1/k-1} + \underline{B} \,.\, \underline{U}_{k-1} \quad \ldots\ldots \; 2.7$$

$$\underline{U}_{k-1} = \underline{C} \,.\, \underline{X}_{k-1/k-1} \quad \ldots\ldots \; 2.8$$

$\underline{K}_{k}$ is Kalman gain matrix

$$\underline{K}_k = \underline{P}_{k/k-1} \; \underline{H} \; [\; \underline{H} \, . \, \underline{P}_{k/k-1} \, . \, \underline{H}'_k + \underline{Q} \;]^{-1} \qquad \ldots\ldots \; 2.9$$

$$\underline{P}_{k/k-1} = \underline{A} \, . \, \underline{P}_{k-1/k-1} \, . \, \underline{A}' + \underline{D} \, . \, \underline{R} \, . \, \underline{D}' \qquad \ldots\ldots \; 2.10$$

$$\underline{P}_{k/k} = [\; \underline{I} - \underline{K}_k \, . \, \underline{H} \;] \; \underline{P}_{k/k-1} \qquad \ldots\ldots \; 2.11$$

Initial conditions : $\hat{\underline{X}}_{0/0} = E [\; \underline{X}_0 \;]$ 2.12

Now innovations are given by

$$\underline{a}_k = \underline{y}_k - \underline{H} \, . \, \hat{\underline{X}}_{k/k-1} \qquad \ldots\ldots \; 2.13$$

It can be used to identify gross error .

Here E - denotes expectation values .

cov. - denotes cross correlation between the parameters .

/ (prime) - denotes transpose of the given matrix

It should be mentioned that the measurements are not used for fault diagnosis directly because we do not know the expectation value of the measurement variables , $\underline{y}_k$.

2.2-B THE INNOVATION PATTERN FOR THE FAULTS -:

The expected pattern of innovations that will be observed after a particular fault occurs at time t , can be computed analytically by making use of the fault model and Kalmann filter equations . But here we shall simulate the fault (only leak) that would occure at the begining of the simulation .The fault model for leak is given below .

2.2- B1 FAULT MODEL (PROCESS LEAK ONLY)

A fault model describes the effect of the fault on the process . Here only one type fault (ie,leak) is considered . The models for other types of faults are given in ref. (13 , 16 , 18 , 19) .

PROCESS LEAK MODEL : A leak of magnitude b in the process unit j that occurs at time t=0 can be modelled as step chage in the state eqations ,ie

$$\underline{X}_{k+1} = \underline{A} . \underline{X}_k + \underline{B} . \underline{U}_k + \underline{b} . \underline{m}_j + \underline{D} . \underline{W}_k \qquad 2.14$$

2.2-B2 EFFECT OF THE FAULT ON THE INNOVATION

The state variable , at any time t=k , depends on the values of the variables at previous times , therefore the net effect of fault on the state variables and the innovations change from time to time . We can compute this effect by making use of appro piate fault model and the filter equations .

The expected value of the innovations for any fault i of magnitude b that can occurs at time t = 0 which is less than the time of interest k can be obtained as ;

$$E[\underline{a}_{k/k-1}] = b\ \underline{G}_{k,i} \cdot \underline{m}_{i}$$

where $\underline{G}_{k,i}$ is one of the signature matrices and they have a general expression which is given as follows ;

$$\underline{G}_{k} = \underline{H}\,[\,\underline{T}_{k} - \underline{A} \cdot \underline{J}_{k}\,]$$

Where ,

$$\underline{T}_{k} = \underline{A} \cdot \underline{T}_{k-1} \qquad \ldots.\ 2.17$$

$$\underline{J}_{k} = \underline{A} \cdot \underline{J}_{k-1} \qquad \ldots.\ 2.18$$

Detailed derivation of these expressions are given in ref. (13 , 16 , 18 , 19) .

Thus the hypothesis of the fault (leak) detection can be formulated as :

<u>FOR NO LEAK</u>

$$\underline{H}_{0} : E[\underline{a}_{k} / \underline{y}_{k-1}] = \underline{0} \qquad \ldots.\ 2.19$$

<u>FOR LEAK</u>

$$\underline{H}_{1} : E[\underline{a}_{k} / \underline{y}_{k-1}] = b \cdot \underline{G}_{k} \cdot \underline{m} \qquad \ldots.\ 2.20$$

2.2-B3 IDENTIFICATION AND ESTIMATION OF LEAK -:

With the hypothesis given by the equations (2.19) & (2.20) we will performed the GEMERAL LIKELIHOOD RATIO (GLR) test to iden-

tify leak . For this we have to calculate the likelihood ratio , which is defined as ;

$$= \frac{Pr(\underline{X}, \underline{\mu}_k)}{Pr(\underline{X}, 0)} \qquad \ldots\ldots \quad 2.21$$

Where ,

$Pr(\underline{X}, \underline{\mu}_k)$ = the probability of obtaining the observed innovations if a leak of magnitude b is present .

$$= [\exp(-.5 \sum^{N} (\underline{a}_k - \underline{\mu}_k)' \cdot \underline{Q}_k^{-1} \cdot (\underline{a}_k - \underline{\mu}_k))] / Kpr \qquad \ldots . \quad 2.22$$

$Pr(\underline{X}, 0)$ = the probability of obtaining observed innovations if no leak is present .

$$= [\exp(-.5 \sum^{N} (\underline{a}_k' \cdot \underline{Q}_k \cdot \underline{a}_k))] / Kpr \qquad \ldots . \quad 2.23$$

$$Kpr = (2 \pi)^{.5Nn} \prod^{N} \left| Qi \right|^{.5}_{i=1} \qquad \ldots\ldots \quad 2.24$$

$$\underline{\mu}_k = b \, \underline{C}_k \cdot \underline{m}_i \qquad \ldots . \quad 2.25$$

$\underline{Q}_k$ = error coverience matrix of $\underline{a}_k$

Nn = no of sampling periods that transpire , subsequent to the occurrence of leak .

Now the maximum likelihood ratio is given by (ref. 18)

$$T = 2 \ln (\underline{X}) = \operatorname{Sup}_i \; T_i \qquad \ldots\ldots \; 2.26$$

Where ,

$$T_i = d_i^2 \; / \; c_i^2 \qquad \ldots\ldots \; 2.27$$

$$d_i = \underline{m}_i' \sum^{N} \underline{G}_{k,i}' \; . \; \underline{Q}_k^{-1} \; . \; \underline{X}_k \qquad \ldots\ldots \; 2.28$$

$$c_i = \underline{m}_i' \sum^{N} (\underline{G}_k' \; . \; \underline{Q}_k^{-1} \; . \; \underline{G}_k) \; . \; \underline{m}_i \qquad \ldots\ldots \; 2.29$$

The maximum value of T_i gives T . Using the principle of likelihood test , the fault which is correspond to T , is identified and it's magnitude is estimated by the corresponding b_i .

2.3 PROCEDURE FOR IDENTIFICATION OF LEAK USING GLR METHOD -:

Leak is detected and estimated using a computer programe . Complete flow chart of the programe is shown in fig. 2.2

FIG 2.1a FAULT 1

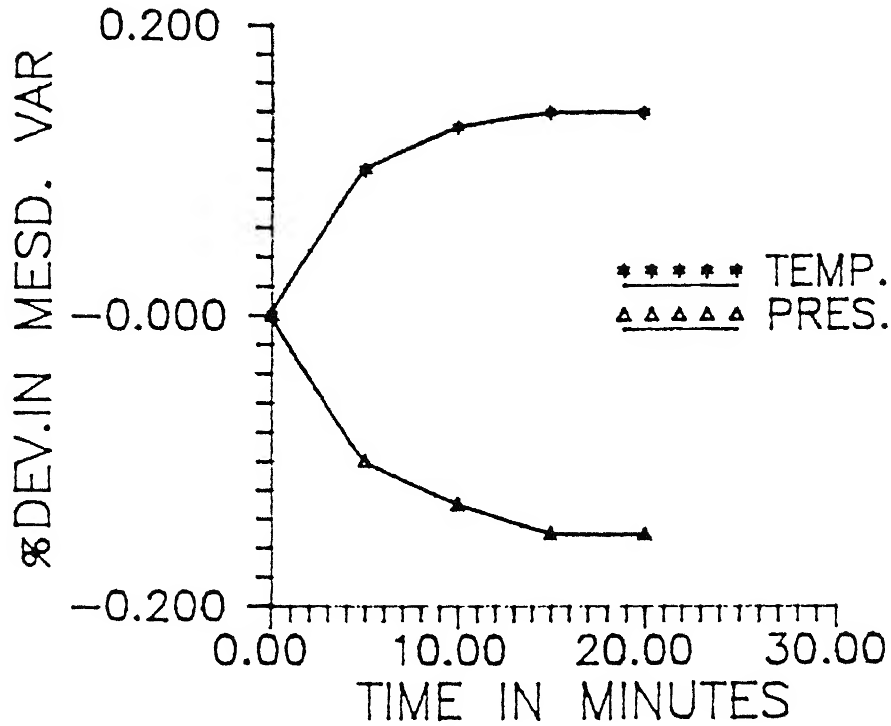
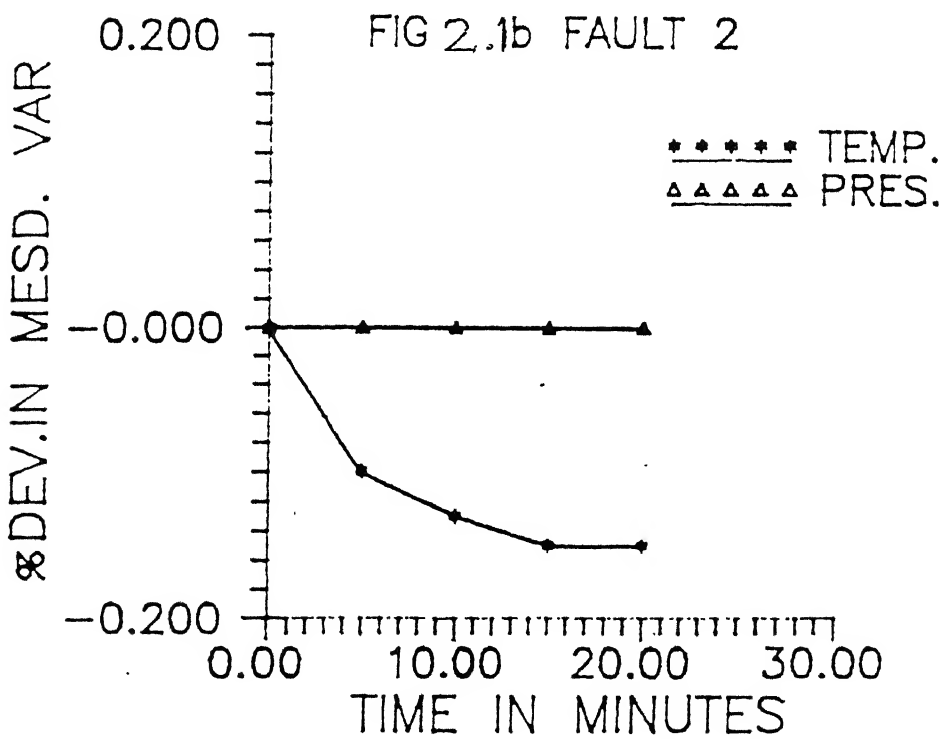


FIG 2.1b FAULT 2



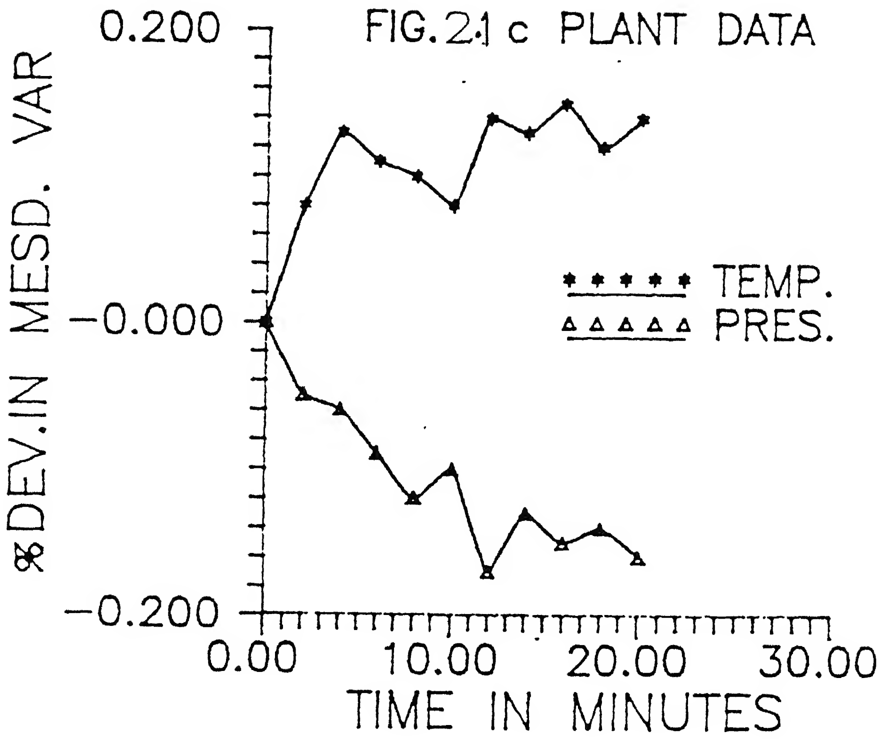


FIG. 2.1 SCHEMATIC PLOTS TO EXPLAIN GLR METHOD PICTORIALLY

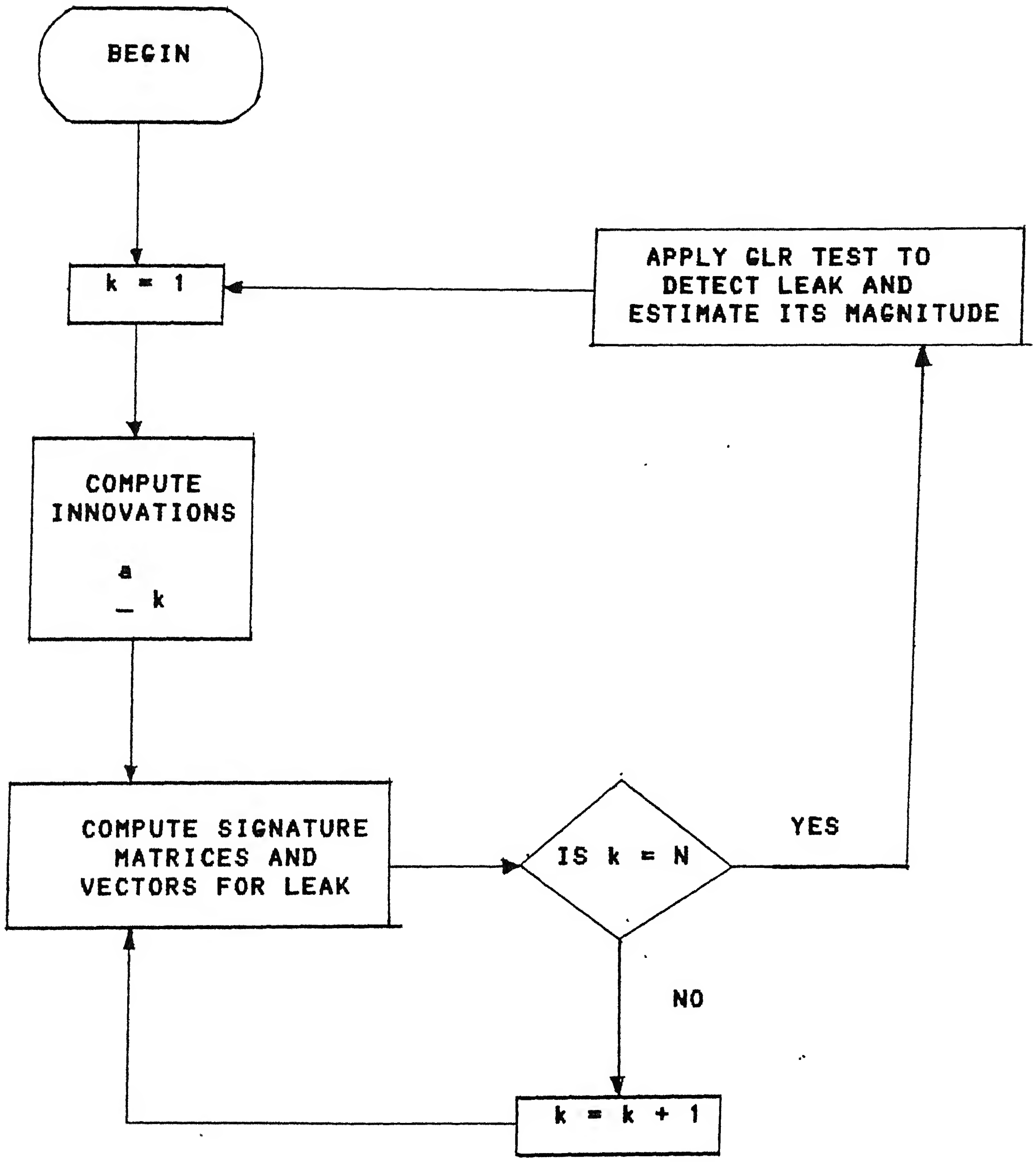


FIG 2.2 : FLOW CHART OF GLR METHOD (simplified)

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CHAPTER - 3

MATHEMATICAL MODELLING OF STEAM GENERATOR

3.1 STEAM GENERATOR -:

The steam generator that has been modelled is a vertical shell and U-tube evaporator. It produces a mixture of water and steam at saturated conditions . Centrifugal moisture separators located above the U-tube bundle , act so as to produces steam of required quality.

A simplified model of the steam generator is developed with the objective of verifying whether SBLOCA can be detected .

3.2 GEOMETRY OF THE MODEL

The steam generator has two cylindrical sections of different cross sectional area as shown in the fig 3.1 . Lower section contains a bundle of U-tube and it has a smaller cross sectional area than the upper section . Pressurized heavy water, which is primary fluid , flows through the U-tube bunddle and water which is secondary fluid , flows through the shell.

3.2-A VARIABLES OF INTEREST -:

Following variables are used in modelling the SG .

i) STATE VARIABLES

- h - water level in shell
- Do2 - density of steam produced
- ΔP - pressure drop in primary coolant tube
- To1 - outlet temperature of primary coolant

ii) MANIPULATED VARIABLES

F1 - flow rate of primary coolant

(It is manipulated to control the level of fluid in primary coolant tube)

Fi2 - inlet flow rate of secondary fluid

(manipulated to control the level of fluid in shell side of the SG)

In addition ,the quality of steam, X which is defined as mass ratio of dry saturated steam to the water vapour mixture , is used . The steam generator model is described in term of deviation variables , ie in term of the deviation of variables from their steady state values . Deviation variables are defined as ;

$\underline{h} = hs - h$

$\underline{Do2} = Do2S - Do2$

$\underline{\triangle P} = PS - P$

$\underline{To1} = To1S - To1$

3.3 ASSUMPTION

i) NEGLIGIBLE SENSIBLE HEAT : Secondary fluid enters the steam generator at it's boiling point at the corresponding pressure Thus the sensible heat transfer to the secondary fluid is zero .

ii) SMALL DEVIATION : The process is assumed that it is operated around normal steady state value , ie , deviation is small .

iii) LINEAR TEMPERATURE DISTRIBUTION :Temperature variation of primary coolant is linear along the length of the U-tube .

iv) EQIDISTRIBUTION OF THERMAL IMBALANCE: Thermal imbalance (B) is the difference between the heat content of in & output streams. This imbalance is due to the accumulation of heat in both the primary and secondary side .It is assumed that this thermal imbalance is share equally by primary coolant and secondary fluid .

3.4 DERIVATION OF THE MODEL -:

3.4-A REDUCED BALANCE EQUATIONS FOR STEAM GENERATOR

a) PRESSURE DROP EQUATION : Mechanical energy balance equation for primary coolant tubes

Using usual meaning of friction factor , f , pressure drop in the tubes is given by :

$$\triangle P = f \cdot \frac{1}{id} \cdot \frac{D1 \cdot V^2}{2}$$

Where V is the velocity of coolant through tubes.

If n is the no of tubes and a - is cross sectional area then

$$\triangle P = f \cdot \frac{1}{id} \cdot \frac{D1 \cdot F1^2}{2 \cdot n \cdot a} \qquad \ldots\ldots\ldots \quad 3.1$$

Using deviation variables and linearizing the above eqution about the normal steady state values we get

$$\underline{\Delta P} = f \cdot \frac{1}{Id} \cdot \frac{D1 \cdot F1S}{n \cdot a} \cdot \underline{F1}$$

$$\underline{\Delta P} = C9 \cdot \underline{F1} \qquad \ldots\ldots\ldots\ldots \quad 3.2$$

b) OVERALL MASS BALANCE FOR THE SECONDARY SIDE OF THE STEAM GENERATOR

Rate of mass in - Rate of mass out = Rate of mass accumulation

$$Fi2 \cdot Di2 - Fo2 \cdot Do2 = \frac{d}{dt} [(L - h) A \, Do2 + h \, A \, Di2] \quad ..3.3$$

Writing the above equation in terms of deviation variables we get

$$(A' \; Di2 - A \; Do2S) \frac{d \underline{h}}{dt} + A \; (L - hS) \frac{d \underline{Do2}}{dt} = Di2 \cdot \underline{Fi2} - Fo2S . \underline{Do2}$$

Do2S . $\underline{Fo2}$ is small and is neglected

Where terms involving product of deviation variables are beglected

$$a1 \cdot \frac{d \underline{h}}{dt} + a2 \cdot \frac{d \underline{Do2}}{dt} = a10 \; \underline{Fi2} + a6 \; \underline{Do2} \quad \ldots\ldots \quad 3.4$$

c) OVERALL THERMAL ENERGY BALANCE IN THE SG

Rate of heat in - Rate of heat out = Rate of heat accumulation in the primary + secondary side

$$\text{or, thermal imbalance (B)} = \frac{d \, [HP]}{dt} + \frac{d \, [HS]}{dt} \qquad \ldots\ldots\ldots\ldots \quad 3.5$$

Using the assumption (iv) and writing the equation in terms of deviation variables we get

$$\frac{1}{2} \cdot \underline{B} = \frac{d\ [\underline{HP}]}{dt} \qquad \ldots\ldots\ldots\ldots \quad 3.6$$

$$\frac{1}{2} \cdot \underline{B} = \frac{d\ [\underline{HS}]}{dt} \qquad \ldots\ldots\ldots\ldots \quad 3.7$$

Now we have to derive an expression for ACCUMUMATION OF HEAT IN PRIMARY AND SECONDARY SIDE

PRIMARY SIDE : Fig 3.1 shows one U-tube of length l and cross sectional area , a . Let us consider a small element of length dx at a distance x from the inlet of the coolant. Now using assumtion (iii) temperature of the element is given by

$$Tx = Ti1 + x \cdot (To1 - Ti1) / l$$

Heat content of the small element is

$$= a \cdot dx \cdot D1 \cdot Cp1 \cdot Tx$$

Total heat content for a single tube is

$$= \int_{x=0}^{x=l} a \cdot D1 \cdot Cp1 \cdot Tx \cdot dx$$

$$= a \cdot D1 \cdot Cp1 \cdot (Ti1 + To1) \cdot l / 2$$

Total heat content for n tubes is given by

$$HP = n \cdot a \cdot D1 \cdot Cp1 \cdot l \cdot (Ti1 + To1) / 2$$

or, $$HP = d4\ (Ti1 + To1)$$

Therefore rate of accumulation of heat in primary coolant tubes in term of deviation variables is given by

$$\frac{d\,\underline{[HP]}}{dt} = d4 \cdot \frac{d\,\underline{Ti1}}{dt} + d4\,\frac{d\,\underline{To1}}{dt} \qquad \ldots\ldots \quad 3.8$$

SECONDARY SIDE : Rate of heat accumulation is given by the equation

$$\frac{d\,[HS]}{dt} = \frac{d}{dt}\,[\,A\ h\ Di2\ Hl + A\ (L - h)\ Do2\ \{\,X\ Hs + (1 - X)\ Hl\,\}\,]$$

Differentiating right hand side after substituting for X.Do2 from eqn. (A 2) and then substituting for X from equation (A 3) in the expression we get

$$\frac{d\,[HS]}{dt} = [\,A\ Di2\ Hl - A\ Hs\ Do2S\ XS - A\ Hl\ (1 - XS)\ Do2\,]\ \frac{d\,h}{dt}$$

$$+\ [\,A\ (L - hS)\ Do2S\ k9\ \{\,Hs / Di2 - Hl / Ds\}]\ \frac{d\,Do2}{dt}$$

Using deviation variables above equation will be

$$\frac{d\,\underline{[HS]}}{dt} = b1 \cdot \frac{d\,\underline{h}}{dt} + b2\,\frac{d\,\underline{Do2}}{dt} \qquad \ldots\ldots \quad 3.8a$$

Now combining equation (3.7) , (A 4) , (A 3) and (3.8a) we get

$$b1\,\frac{d\,\underline{h}}{dt} + b2\,\frac{d\,\underline{Do2}}{dt} = \frac{1}{2}\,[\,b6\ \underline{Do2} + b8\ \underline{To2} + b9\ \underline{F1} + b10\ \underline{Fi2} + b11\ \underline{Ti1}\,] \qquad \ldots\ldots \quad 3.9$$

Combining equation (3.6) , (A 4) , (A 3) and (3.8) we get

$$d4 \frac{d\,\underline{Ti1}}{dt} + d4 \frac{d\,\underline{To1}}{dt} = \frac{1}{2}[\, b6\, \underline{Do2} + b8\, \underline{To2} + b9\, \underline{F1} + b10\, \underline{Fi2} + b11\, \underline{Ti1}\,]$$

$$\text{or,}\quad \frac{d\,\underline{To1}}{dt} = A(4,2)\, \underline{Do2} + A(4,4)\, \underline{To1} + B(4,1)\, \underline{F1} + B(4,2)\, \underline{Fi2} + D(4,1)\, \underline{Ti1} \quad \ldots\ldots \quad 3.10$$

seperating derivative terms from the equations (3.4) and (3.9) , that is , doing (3.4).b2 - (3.9).a2 we get

$$\frac{d\,\underline{h}}{dt} = A(1,2)\, \underline{Do2} + A(1,4)\, \underline{To1} + b(1,1)\, \underline{F1} + B(1,2)\, \underline{Fi2} + D(1,1)\, \underline{Ti1} \quad \ldots\ldots \quad 3.11$$

and doing (3.9).a1 - (3.4).b1 we get

$$\frac{d\,\underline{Do2}}{dt} = A(2,2)\, \underline{Do2} + A(2,4)\, \underline{To1} + B(2,1)\, \underline{F1} + B(2,2)\, \underline{Fi2} + D(1,2)\, \underline{Ti1} \quad \ldots\ldots \quad 3.12$$

3.4-B STATE SPACE REPRESENTATION -:

a) STATE SPACE EQUATIONS : Let the derivative ot a variable(say h) at time k is

$$\left.\frac{d\,\underline{h}}{dt}\right|_{k} = \frac{\underline{h}_{k+1} - \underline{h}_{k}}{t}$$

where t is small discretized time

Using the above defination and equation (3.11) , (3.12) , (3.2) and (3.10) the state space matrix eqation of the model is

$$\begin{bmatrix} \underline{h} \\ \underline{Do2} \\ \underline{\Delta P} \\ \underline{Tol} \end{bmatrix}_{k+1} = \begin{bmatrix} 1.0 & A(1,2).t & 0.0 & A(1,4).t \\ 0.0 & 1+A(2,2).t & 0.0 & A(2,4).t \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & A(4,2).t & 0.0 & 1+A(4,4).t \end{bmatrix} . \begin{bmatrix} \underline{h} \\ \underline{Do2} \\ \underline{\Delta P} \\ \underline{Tol} \end{bmatrix}_{k}$$

$$+ \begin{bmatrix} B(1,1).t & B(1,2).t \\ B(2,1).t & B(2,2).t \\ c9 & 0.0 \\ B(4,1).t & B(4,2).t \end{bmatrix} \begin{bmatrix} \underline{F1} \\ \underline{Fi2} \end{bmatrix}_k + \begin{bmatrix} D(1,1).t \\ D(2,1).t \\ 0.0 \\ D(4,1).t \end{bmatrix} \underline{Ti1}_{\ k}$$

or, $$\underline{X}_{k+1} = \underline{A}\,\underline{X}_k + \underline{B}\,\underline{U}_k + \underline{D}\,\underline{W}_k \qquad \ldots\ldots \quad 3.13$$

c) MESUREMENT EQUATIONS

$$\underline{y}_k = \underline{H}\,\underline{X}_k + \underline{V}_k \qquad \ldots\ldots \quad 3.14$$

where $\underline{y}_k = \begin{bmatrix} \underline{h} \\ \underline{\Delta P} \end{bmatrix}_k$

$$\underline{H} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$\underline{V}_k$ = noise in the measurements

d) CONTROL LAW

$$\underline{U}_k = \underline{C}\,\underline{y}_k \qquad \ldots\ldots\ldots \quad 3.15$$

where $\underline{C} = \begin{bmatrix} 0.0 & @1 \\ @2 & 0.0 \end{bmatrix}$

3.4-C STABILITY ANALYSIS -:

Combining state space equation with the control law and measurement equation we get

$$\underline{X}_{k+1} = (\underline{A} + \underline{B}.\underline{C}.\underline{H})\,\underline{X}_k + \underline{D}\,\underline{W}_k$$

If noise equals to zero , we have

$$\underline{X}_1 = (\underline{A} + \underline{B}.\underline{C}.\underline{H})\,\underline{X}_0$$

$$\underline{X}_2 = (\underline{A} + \underline{B}.\underline{C}.\underline{H})\,\underline{X}_1 = (\underline{A} + \underline{B}.\underline{C}.\underline{H})^2\,\underline{X}_0$$

-- -- -- -- -- -- -- --

$$\underline{X}_{K+1} = (\underline{A} + \underline{B}.\underline{C}.\underline{H})^{k+1} .\ \underline{X}_0$$

From the above equation it is obvious that the system will be stable iff $(A + B.C.H)$ matrix have eigen values less then unity . Thus we have to find out suitable values of @1 , @2 and t , that will make the system stable ,ie, $(A + B.C.H)$ matrix have eigen values less then unity .

a) EXPRESSION FOR $(\underline{A} + \underline{B}.\underline{C}.\underline{H})$ MATRIX

$(\underline{A} + \underline{B}.\underline{C}.\underline{H}) =$

$$\begin{bmatrix} 1+B(1,2).@2.t & A(1,2).t & B(1,1).@1.t & A(1,4).t \\ B(2,2).@2.t & 1+A(2,2).t & B(2,1).@1.t & A(2,4).t \\ 0.0 & 0.0 & c9.@1 & 0.0 \\ B(4,2).@2.t & A(4,2).t & B(4,1).@1.t & 1+A(4,4).t \end{bmatrix}$$

b) A computer programe is used to compute eigen values. Programe logic is shown in fig 3.2 .

c) RESULT OF STABILITY ANALYSIS : System will be in the most stable condition when maximum absolute value of eigen values is far less then

unity . From the computed result it is seen that the most stable condition is :

$$t = 1.0 \text{ sec}$$

$$\theta 1 = 0.968E-08$$

$$\theta 2 = 0.239E-03$$

3.4-D LEAK MODEL -:

Loss of primary coolant through a leak or break within the primary cooling system (PHT-loop) is called loss of coolant. If liquid injection into the system is insufficient to cope up with this problem , it will cause an accident, called loss of coolant accident (LOCA). Depending up on the size of the leak it is classified into three catagories ;

- Small break LOCA (leak dia < 0.005 m)
- Medium LOCA (.005<leak dia < .025 m)
- Large break LOCA (leak dia > .025 m)

The probability of occurrence of such a leak is very small but once it occurs it has high risk because it's consequence could include the risk of major release of radioactive materials . So PHT loop should be designed aganist such fault . Thus it is a designed basis accident (DBA) . Table 3.T1 (ref. 6 Pp 292) shows the leak size of different LOCA, their probability of occurrence, percentage of fluid loss and no of injecting system should be operated to avoid bad consequence.

From the table it is obvious that the occurrence of SBLOCA is higher and our consideration is restricted to such a leak. When such a leak occurs in a tube it has several consequence events depending upon size , tube size , orientation of the tube (horizontal or vertical), pressure difference at the escaping point , velocity of the fluid and nature of the fluid . Experimantally it is seen that phase separation

will be minimum when leak size is small , tube is vertical , pressure difference at the escaping point is small , velocity of fluid is high and fluid is highly viscous (ref. 3 Pp 15 - 19) . In our case , all the points except last one are in favour of no phase separation. Thus we can assume that no leak equations are equaly valid for leak model except the flow rate of primary coolant , F1 , should be (F1 - b) . where b is the magnitude of the leak .

Now the state space representation of the LEAK MODEL is ;

$$\underline{X}_{k+1} = \underline{A} . \underline{X}_k + \underline{B} . \underline{U}_k + \underline{D} . \underline{W}_k + b . \underline{m} \qquad \ldots\ldots\ldots \quad 3.16$$

where the leak matrix,

$$\underline{m} = \begin{bmatrix} B(1,1).t \\ B(2,1).t \\ 0.0 \\ B(4.1).t \end{bmatrix} = \begin{bmatrix} -.108E+00 \\ .225E+02 \\ -.131E+06 \\ -.217E+02 \end{bmatrix}$$

3.5 NUMERICAL VALUES OF THE MATRICES -:

STATE TRANSITION MATRIX ($\underline{A}$)

$$\begin{bmatrix} .001E+0 & .120E-3 & .000E+0 & -.838E-3 \\ .000E+0 & .654E+0 & .000E+0 & -.175E+0 \\ .000E+0 & .000E+0 & .000E+0 & .000E+0 \\ .000E+0 & .567E-2 & .000E+0 & .831E+0 \end{bmatrix}$$

MEASUREMENT MATRIX ($\underline{H}$) :

$$\begin{bmatrix} .100E+0 & .000E+0 & .000E+0 & .000E+0 \\ .000E+0 & .000E+0 & .000E+0 & .000E+0 \end{bmatrix}$$

CONTROL MATRIX ($\underline{B}$)

$$\begin{bmatrix} .108E+00 & .331E+0 \\ -.225E+2 & .649E+2 \\ .131E+6 & .000E+0 \\ .217E+2 & .745E+2 \end{bmatrix}$$

PROCESS NOISE MATRIX ($\underline{D}$)

$$\begin{bmatrix} .838E-3 \\ -.175E+0 \\ .000E+0 \\ .124e+1 \end{bmatrix}$$

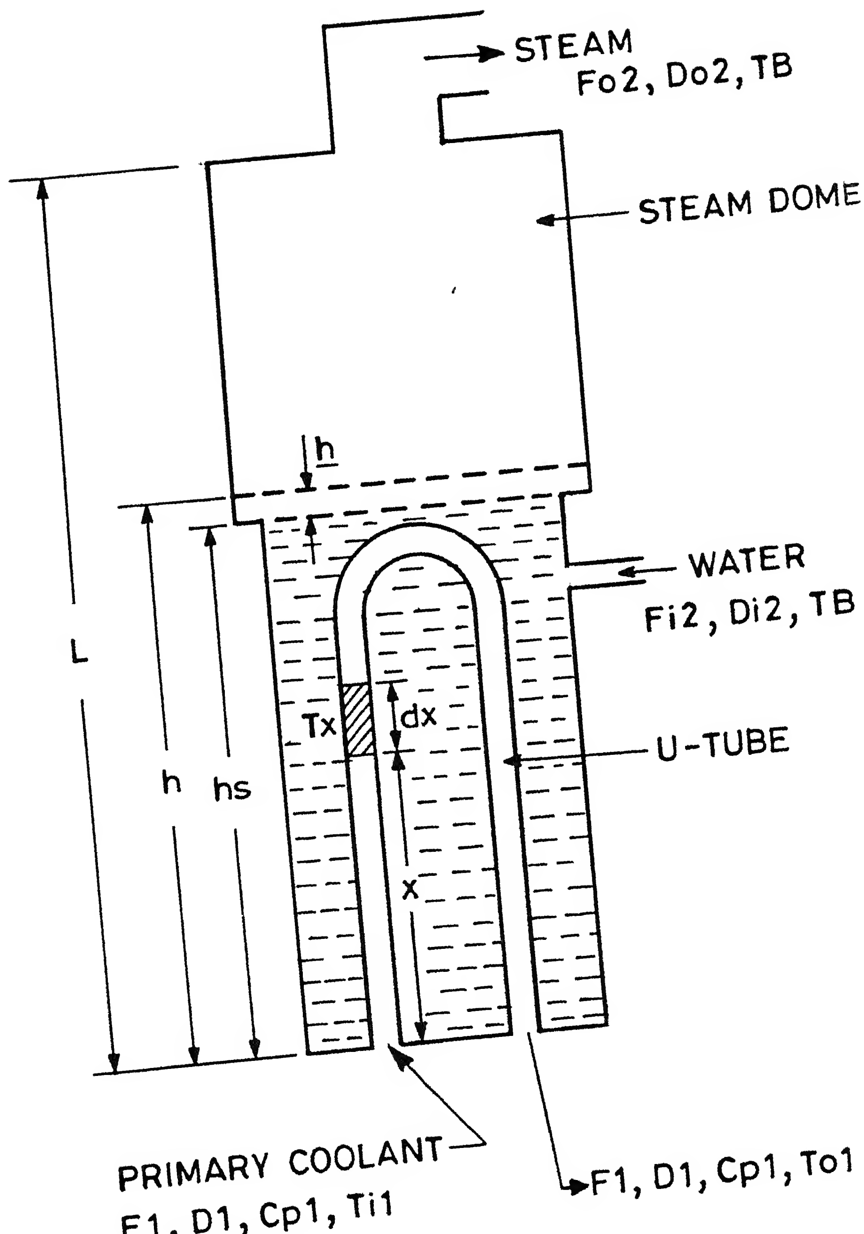

Fig. 3.1 U-tube steam generator.

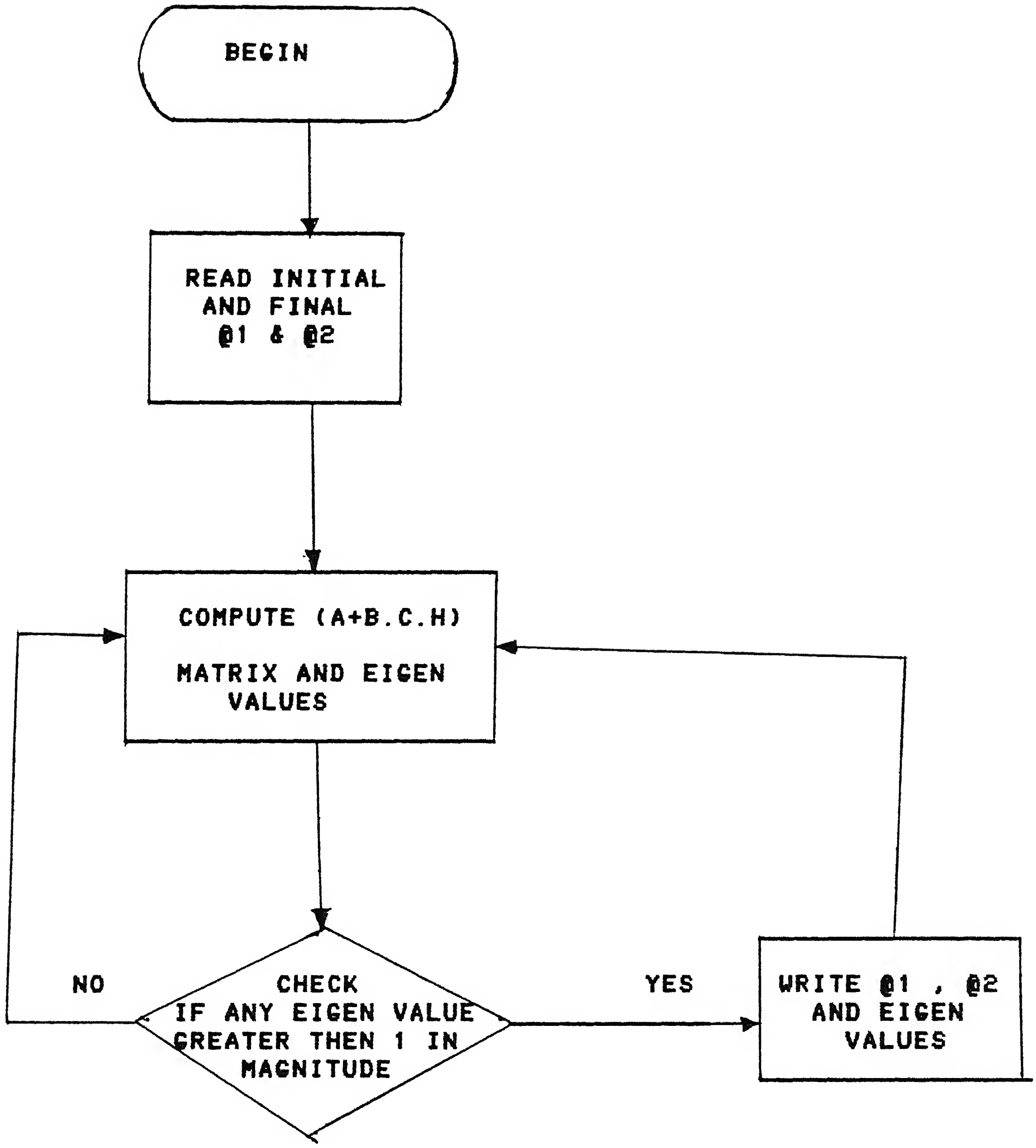

FIG 3.2 : FLOW CHART OF STABILITY ANALYSIS

TABLE - 3.T1

CHARACTERISTICS OF LOCA AND FUNCTION OF THE SAFETY SYSTEM

	Large break LOCA	Intermediate LOCA	small break LOCA
Break size (M^2)	4E-2 - 1E-1	8E-3 - 4E-2	< 8E-3
Ave. probability of occurrence	1E-4 / a	8E-4 / a	3E-3 / a
% loss of coolant	10 - 15	2 - 10	< 2
Safety system function (injection)			
- Accumulator	3 of 4	2 of 4	—
- Auxiliary feed water	—	—	1 or 2 of 4

CHAPTER -: 4

RESULTS AND DISCUSSION

4.1 RESULTS -:

The simulation has been done over the first 500 seconds of the accident , during which the operator has yet taken no corrective action . It is a real time simulation which predicts dynamic response to both the normal and abnormal operating conditions . The process model as given by the equations (3.13 - 3.16) are used for simulation . Since all the variables in the process model are deviation variables , ie (true value - normal value) , henceforth in the discussion all variables mentioned are deviation variables .

At first the process is simulated without a leak to get the system dynamics . The procedure adopted is as follows:

- initialize the state and control variables .
- compute process noise by generating random error from multivariate normal distribution with zero mean and coverience matrix $\underline{R}$
- compute state variables by equation (3.13)

- generate measurement noise by same procedure as in second step .

- compute measurement variables by equation (3.15)

- use kalman filter to estimate the state vector and error coverience matrix .

- obtain control inputs at each time using equation (3.14)

The true values of the measured variables are obtained for 500 time steps ,ie for 500 seconds , since each time step equals to one second . Fig. 4.1 shows the percent deviation of the measured variable pressure with time , which clearely indicates that the values are randomly distributed around zero mean (ie normal value) .

Now for the same type of simulation a leak of different magnitude is incorporated in the dynamic model . Since the objective is to detect SBLOCA (ie manitude of the leak is less than 2.0% of total flow rate) , the leak magnitude is varied between 0.01 and 2.0% . Simulation is done for 100 times for each leak size . Table 4.T1 shows the magnitude of different leaks and accuracy with which it can be detected .

From the table it can be seen that the method can detect leak of magnitude as low as 0.25% of total flow rate with a probability of 0.9 (ie 90 times out of 100 times) . For a leak of magnitude 0.1% , the percent deviation of pressure is shown in the fig. 4.2 . From the figure it is clear that the percent deviation of total allowed deviation (maximum deviation which can be controlled) is varying around

zero . This is the reason for not detecting this magnitude of the leak . Fig. 4.3 shows the percent deviation of pressure for a leak of magnitude 1.0% of total flow rate . The figure shows that the pressure will drop abruptly after 4.0 seconds and then starts oscillating around 20.0% of the total allowed deviation . Thus the GLR method can detect this magnitude of the leak .

Fig. 4.4 shows the percent deviation of pressure for different magnitude of leaks ; and fig. 4.5 shows the percent deviation of SG-water level . Both the figures show that the occurrence of leak effects the variables upto certain period of time and then the variables start oscillating around some "pseudo steady state" value . Thus the dynamics is similar to the response of a second order "single input-single output" (SISO) system to the step input . Now , if the time lapses by the system during which the variable should change by 66.6% of total change is response time then for pressure drop it is 5.0 seconds in all cases . Thus the response time for the pressure drop is more or less constant . This can be explained as follows ; the occurrence of leak can be viewed as step input to the system . Now the response time will depend on the time that should be taken by the occurrence of leak to effect the flow rate of heavy water at the outlet of the U-tube . Since magnitude of different leaks are small compared to total flow rate of heavy water , the velocity of water is more or less constant and it will take equal time to effect the outlet flow rate of the primary coolant (heavy water) at the outlet of the U-tube and

consequently the response time will be same .

Response time for pressure is 5.0 seconds which is very small but comparable to the propagation time from inlet to the outlet as explain below ;

total cross sectional area of U-tubes(n.a)=1950*8.92RE-5 M^2

length of U-tubes (1) = 12.8 M

mass flow rate of heavy water (m1) = 380.21 Kg / S

density of heavy water (D1) = 1100 Kg / M^3

Now time taken by heavy water to reach to the outlet of U-tube starting from inlet of the U-tube

$$= \frac{1 \,.\, n.a \,.\, D1}{m1}$$

$$= \frac{12.8 * (1950 * 8.92E-5) * 1100}{380.21}$$

$$= 6.4 \text{ S}$$

If it is assumed that the occurrence of the leak will effect the system only when it's effect reaches to the outlet of the U-tube , expected response time will be 6.4 seconds . This is in close aggrement with the predicted value (5.0 seconds) .

From the figure (fig. 4.4) it is obvious that the higher magnitude of leak , which will be viewed as a step input , effects the system to higher extent , ie the "pseudo steady state" will be far away from original steady state value . This is very similar to the response of a second order SISO

system to different step inputs .

Fig. 4.5 shows that the response time for water level which depends upon the magnitude of the leak and in fact , higher the magnitude of the leak lower will be the response time . This is because higher magnutude of leak will effects the water level quickly due to radical change of rate of heat transfer and have low response time . Other things like effect of magnitude of leak on the new "pseudo steady state" can be explained as before . The response time for change of SG-water level is 25.0 seconds (Fig 4.5) .

From the Fig. 4.4 & Fig. 4.5 one can notice that the response time for level (25.0 seconds) is higher than the response time of pressure (5.0 seconds) . This is because the occurrence of leak has direct effect on pessure and it has secondary (indirect) effect on the level . The response time are very low compare to the response time of most of the chemical plants . This is because of very high velocity of the primary coolant through the U-tubes .

4.2 SCOPE OF THE MODEL AND THE METHOD

Regarding the steam generator model , a number of questions can be considered more closely . Is the model accurate enough to represent the real situation or does it need a more accurate model and if so , what is the cost of computation ? Nonthless , the model as it is presented is quite simple , computationally

fast and gives satisfactory results in the steady state conditions and for the case of SBLOCA (magnitude of the leak less than 2.0% of the total coolant flow rate) . Thus such a model can be used with resonable confidence in numerous applications, such as steam generator primary tube break simulation .

Regarding the performance of the method (GLR) , two important things should be considered simultaneously , the accuracy with which it can be detect SBLOCA and secondly , the delay time ie the time delay to detect the leak after the occurrence of the leak . The performence of the method is quite good because it can detect a leak of magnitude as low as 0.25% of total flow rate with 90% accuracy . And the delay time is only 10 - 15 seconds .

Finally it can be concluded that the method can be used satisfactorily along with the suggested simplifications to detect SBLOCA .

4.3 SCOPE OF THE WORK

The model is not without its drawbacks . The primary disadvantage to the model is an inability to handle two phase conditions within the primary loop . Attempts to remedy this shortcoming should be made . Thus one can study the SG unit with a more realistic model . Another direction of the work is to simulate the complete loop . For this , one needs to model the intermediate feed pump and pipe lines and couple them together to get

a consolidated model which can detect the leak in the entire PHT loop .

In the design of the degital controller it is assumed that it follows linear control law , which is not always true , ie the transition from one steady state to another steady state . The GLR technique will not work for transition of the plant from one steady state to another . Effect of all states variables on the control law also can be varified .

So far the GLR method is used in nuclear industry to detect the sensor failures and biases . Here in this work, it has been shown that the GLR technique can successfully be used to detect LOCA specially SBLOCA in the SG of the PHT loop . The detection of SBLOCA is critical as it may lead to an accident . Also mechanically its detection is difficult . The use of GLR method is illustrated in this respect and also got satisfactory perfor-mence of the method in detecting the SBLOCA .

The method applied here can detect one fault at a time . Methods can can be devoloped to identify multiple faults (ref-18) of any type . Some other faults of greater importance in a nu-clear plant can be modelled such as coolant pump trip , abnormal valve beheviour , turbine trip auxiliary feed water failures , etc . Thus one can study the performence of the method in actu-al situations .

This technique can also be developed for the actual measure-ment data instead of the innovations . For this further detailed study is needed . Finally an expert system to detect SBLOCA can be developed combining the results of the GLR method with experi-mental knowledge as well as information from other sources .

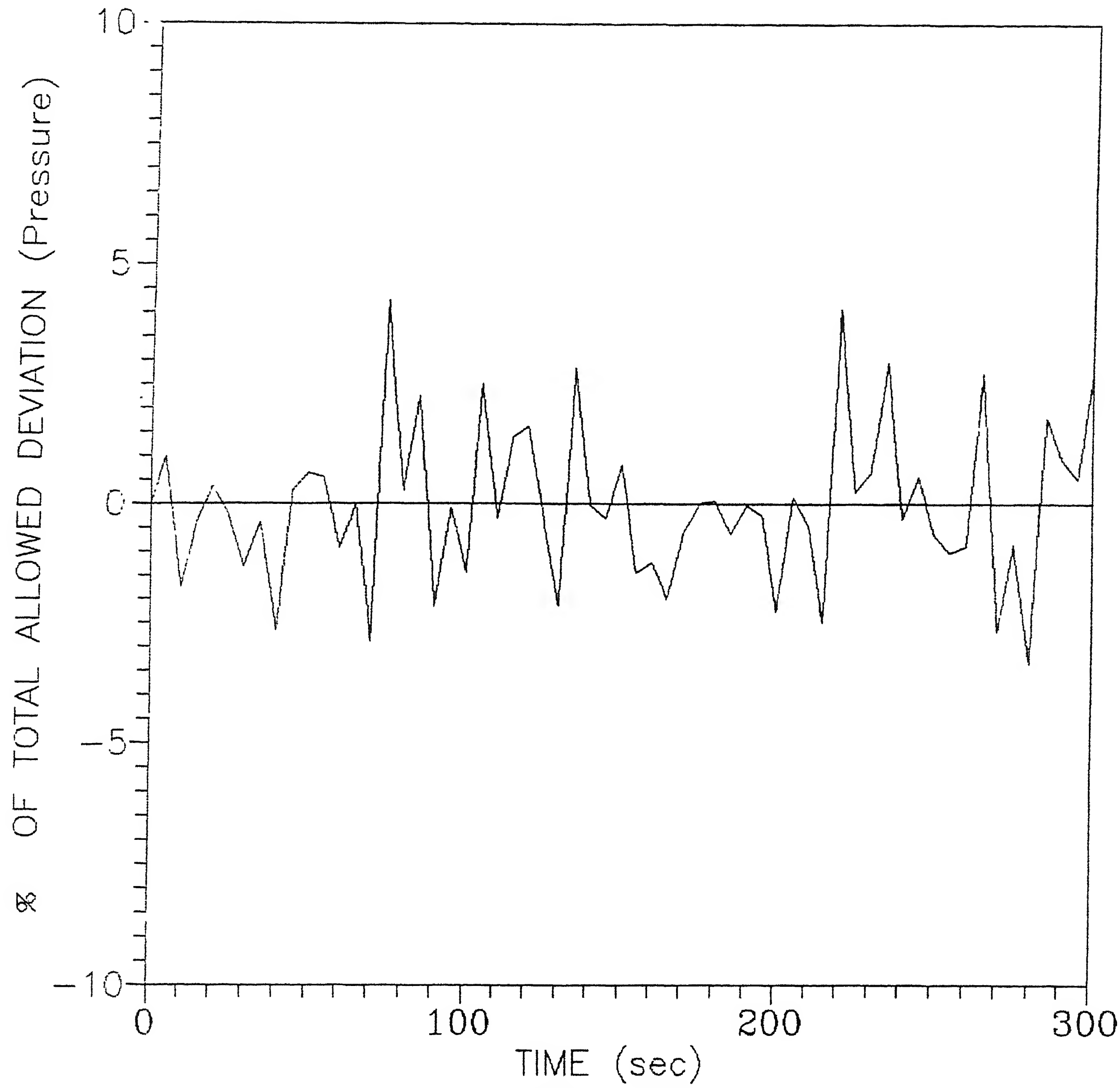

Fig 4.1 : % DEVIATION OF A MEASURED VARIABLE (Pressure) FOR NO LEAK

TABLE -4.T1

PERFORMA NCE OF THE GLR METHOD #

Magnitude of Leak in %	NO. of times Detected Out of 100 Times	% Accuracy
0.01	1	0.02
0.10	6	0.06
0.25	90	0.90
0.50	91	0.91
1.00	96	0.96
1.50	98	0.98
2.00	98	0.98

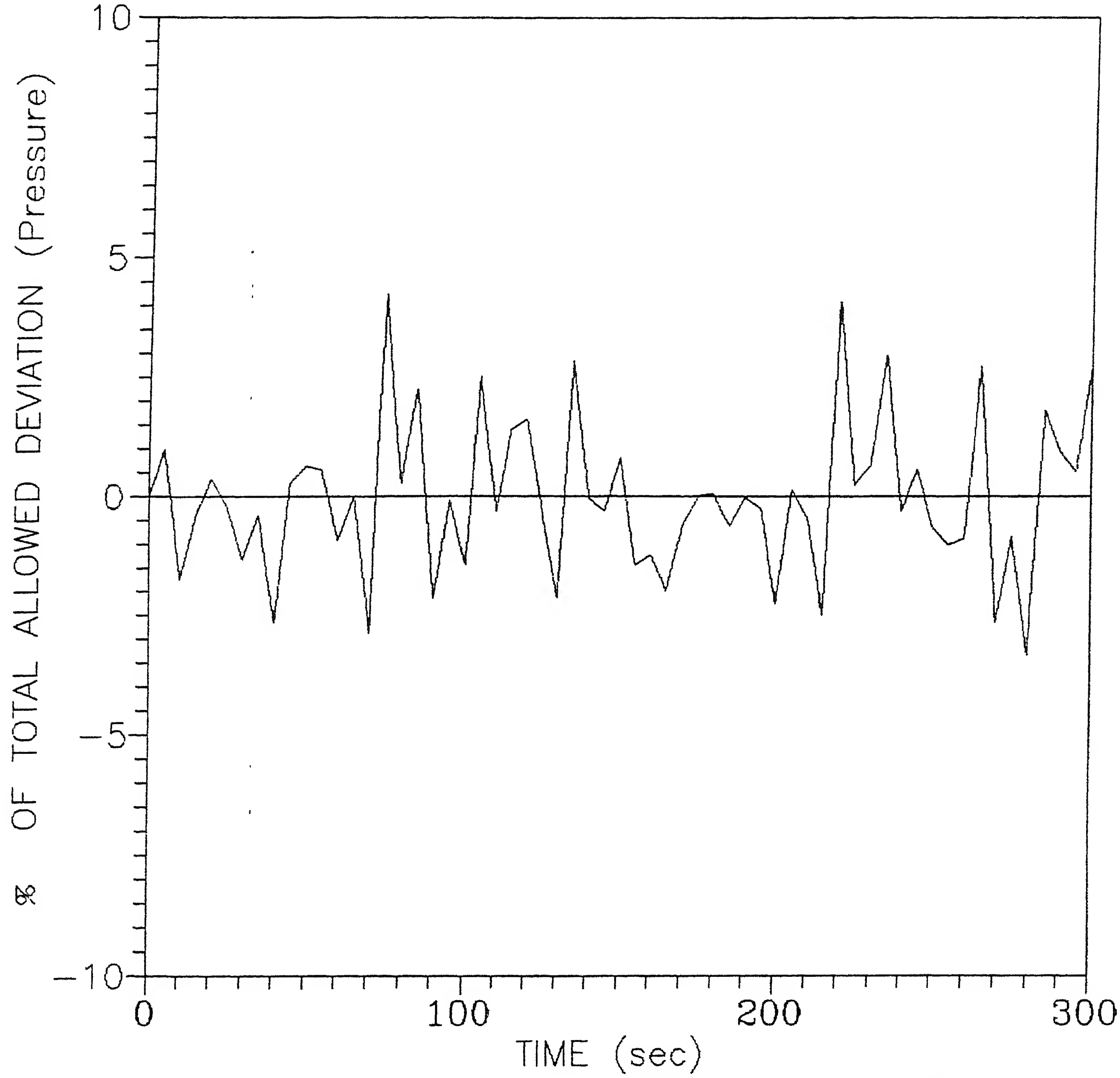

Fig 4.2 : % DEVIATION OF A MEASURED VARIABLE (Pressure)
FOR LEAK = 0.1%

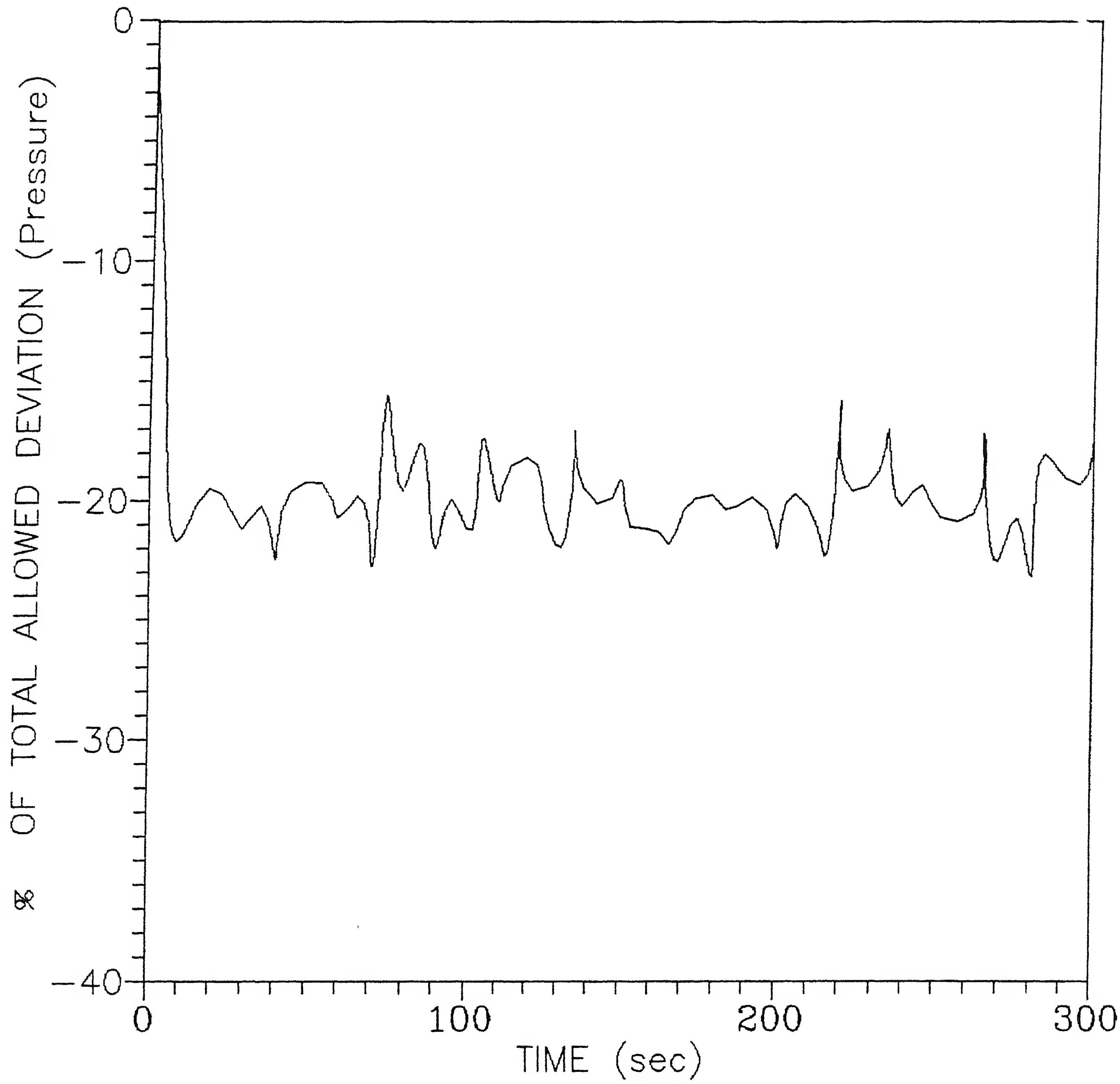

Fig 4.3 : % DEVIATION OF A MEASURED VARIABLE (Pressure)
FOR LEAK = 1.0%

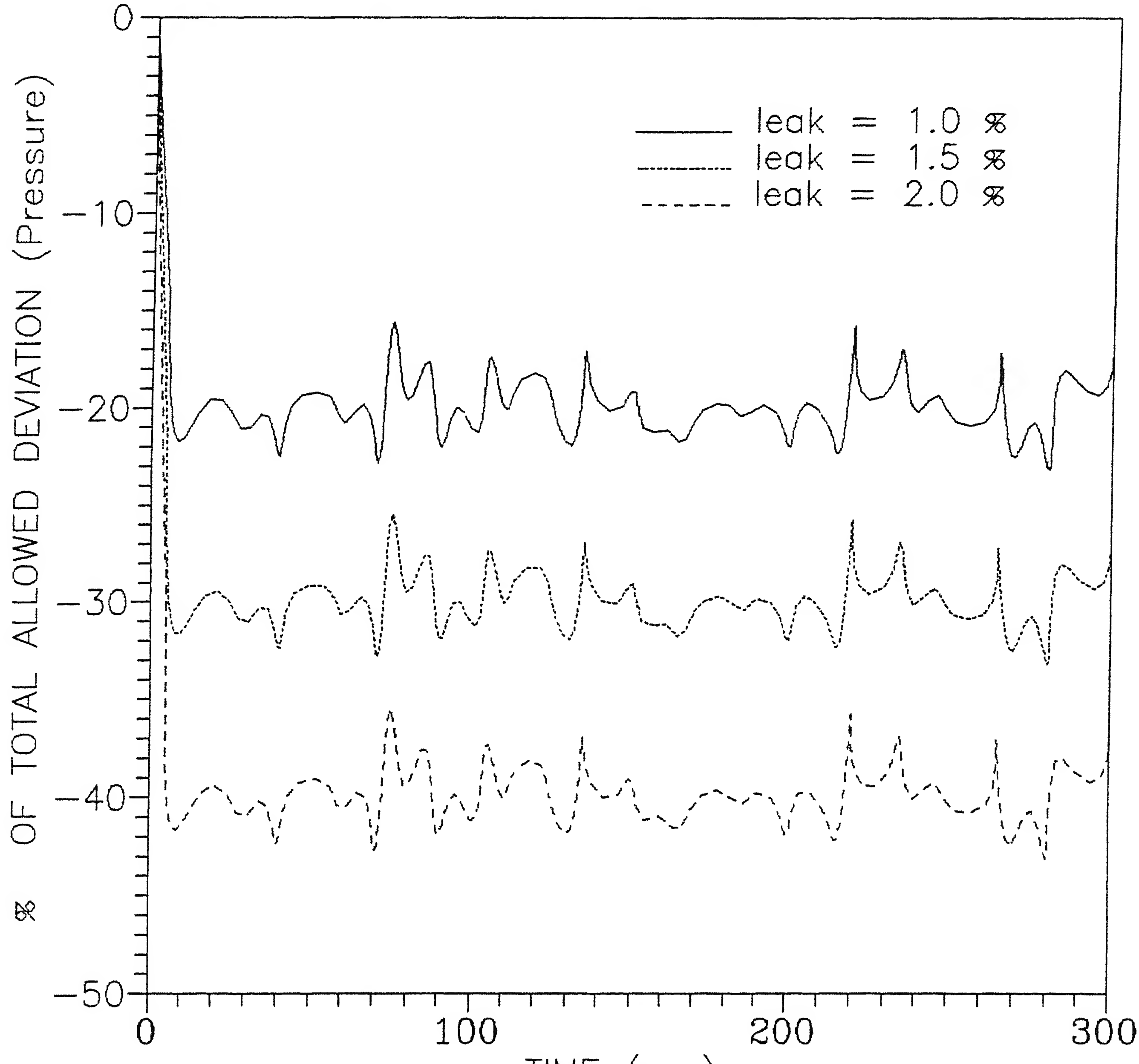

Fig 4.4 : % DEVIATION OF A MEASURED VARIABLE (Pressure) FOR DIFFERENT MAGNITUDE OF LEAKS

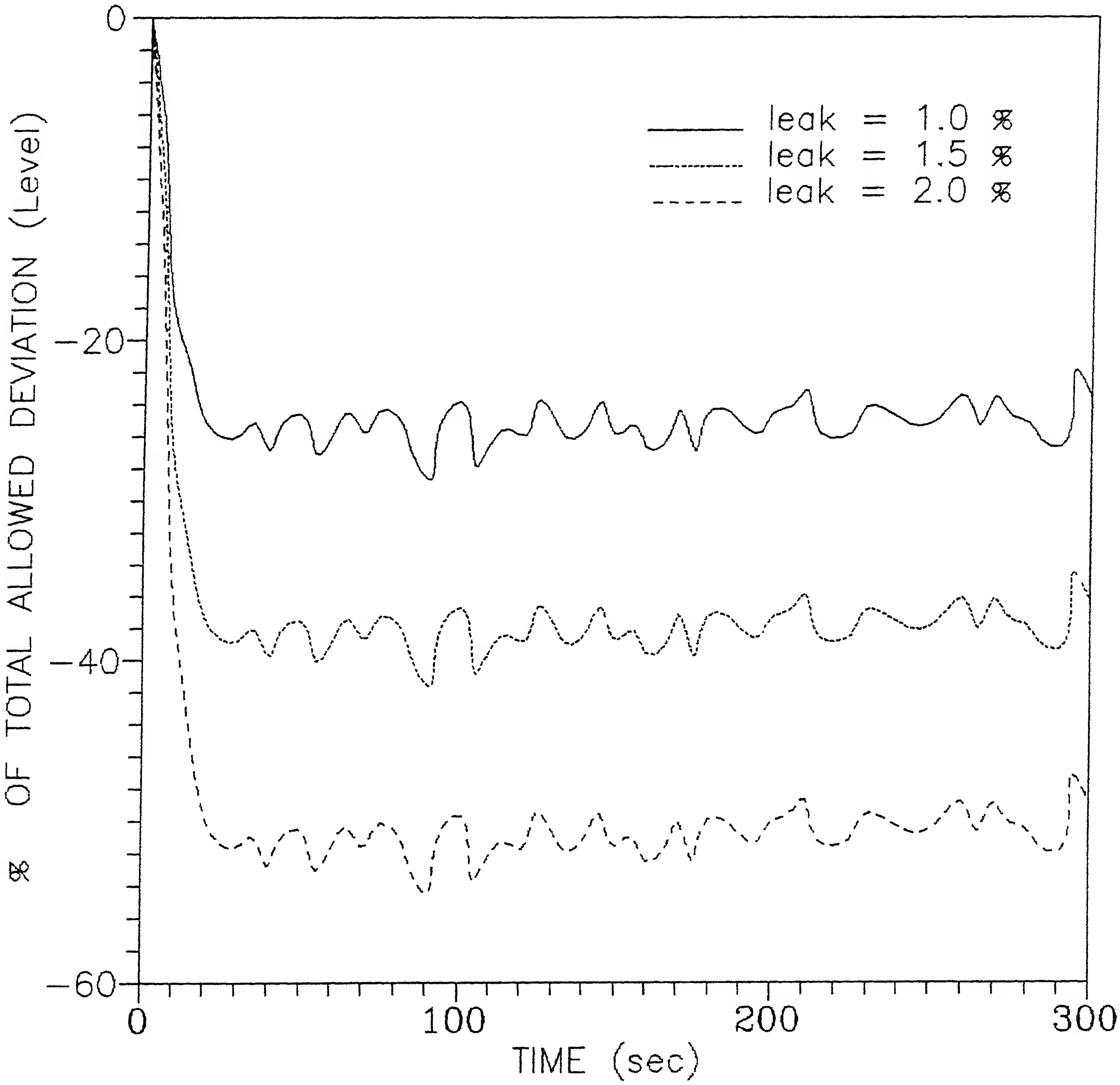

Fig 4.5 : % DEVIATION OF A MEASURED VARIABLE (Level) FOR DIFFERENT MAGNITUDE OF LEAKS

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APPENDIX

A.1 CORRELATION BETEWEEN X & Do2 -:

From the defination of steam quality we have ;

mass flow rate of dry steam = steam quality X (total mass flow rate of vapour-water mixture

ie, $mg = X \;.\; Fo2 \;.\; Do2$

and $ml = (1 - X).\; Fo2.\; Do2$

Total volumetric flow rate = flow rate of steam + water

ie, $Fo2 = mg \,/\, Ds + ml \,/\, Di2$

combining above three equations we get

$$1 \,/\, Do2 = X \,/\, Ds + (1 - X) \,/\, Di2$$

$$\text{or,} \quad X = \frac{Ds \;.\; (Di2 - Do2)}{Do2.\; (Di2 - Ds)} \qquad \ldots\ldots\ldots\ldots \qquad (A1)$$

$$\text{and,} \quad X.Do2 = \frac{(Di2 - Do2).Ds}{(Di2 - Ds)} \qquad \ldots\ldots\ldots\ldots \qquad (A2)$$

Writing (A 1) in term of deviation variables we get

$$(\underline{X} + XS) = \frac{Di2 \;.\; Ds}{(DI2 - Ds).(Do2S + \underline{Do2})} + \frac{Ds}{(Di2 - Ds)}$$

$$= \frac{Di2 \;.\; Ds}{(Di2 - Ds).Do2S} \;.\; 1 + \frac{\underline{Do2}}{Do2S} - \frac{Ds}{(Di2 - Ds)}$$

$$= \frac{Di2 \;.\; Ds}{(Di2 - Ds).Do2S} \;.\; 1 - \frac{\underline{Do2}}{Do2S} - \frac{Ds}{(Di2 - Ds)}$$

(neglecting higher terms)

At steady state deviations are zero , thus from the above equation we get

$$XS = \frac{Di2 \, . \, Ds}{(Di2 - Ds).Do2s} - \frac{Ds}{(Di2 - Ds)}$$

Combining above two equations we get

$$\underline{X} = - \frac{Di2 \, . \, Ds}{(Di2 - Ds0).Do2S} \, . \, \underline{Do2}$$

$$\text{or,} \quad \underline{X} = k9 \, . \, \underline{Do2} \qquad \ldots\ldots\ldots \qquad (A3)$$

A.2 EXPRESSION FOR THERMAL IMBALANCE IN THE STEAM GENERATOR -:

Thermal imbalance at any time in the SG is defined as the difference of heat content between incoming and outgoing streames ie

$$\begin{aligned} B &= \text{Rate of total heat in} - \text{rate of total heat out} \\ &= (Fi2.Di2.Hl + F1.D1.Cp1.Ti1) - (Fo2.Do2.(X.Hs + (1-X)Hl) + F1.D1.Cp1.To1) \end{aligned}$$

Using deviation variables and equqtions (A 1) & (A 2) we get

$$\begin{aligned} \underline{B} = & -Fo2S.Do2S.(Hs - Hl).k9. \, \underline{Do2} - F1S.D1.Cp1. \, \underline{To1} - D1.Cp1.(Ti1S \\ & - To1S).\underline{F1} - Fo2S \, (Hs - Hl).XS.\underline{Do2} + Di2.Hl. \, \underline{Fi2} + F1S.D1.Cp1. \, \underline{Ti1} \end{aligned}$$

$$\text{or,} \quad B = b6. \, \underline{Do2} + b8. \, \underline{To1} + b9. \, \underline{F1} + b10. \, \underline{Fi2} + b11. \, \underline{Ti1} \qquad \ldots . \quad (A4)$$

A.3 CALCULATION OF THE ELEMENTS OF MATRICES -:

Nuclear power plant can be operated at any one of the following stages ;

- steady state operation with full load
- steady state operation with reduced load

Our model can be used for both the cases . But here only the former case is analyse , ie , the elements of matrices are calculated for steady state condition . Table A-1 shows the value of variables at steady state condition . And table A-2 contains values of constant parameters . Different constant coefficients of the modelled equations are calculated based on these tables . Calculation is as follows .

a)

$$a1 = (A' . Di2 - A . Do2S)$$

$$= (1.644 * 852.5 - 3.973 * 18.602)$$

$$= 1327.79 \ Kg / m$$

$$a2 = A.(L - hS)$$

$$= 3.973 * (8.0 - 6.4)$$

$$= 6.356 \ M^3$$

$$a6 = - Fo2S = -2.04 \ M / S$$

$$a10 = Di2$$

$$= 852.5 \ Kg / M^3$$

$$b1 = A' . Di2 . Hl - A . Do2S [Hs .XS + (1 - XS) . Hl)$$

$$= 1.644 * 852.5 * 1085.36 - 3.973 * 18.602 [28o1.5 * .9 + (1-.9) * 1085.36]$$

$$= 1326996.02 \ KJ / M$$

$$b2 = A . (L - hS) . Do2S . k9 . (Hs / Di2 - Hl / Ds)$$

$$= 3.973 * (8.0 - 6.4) * 18.602 * (- 0.04946) * (2801.5 / 852.5 - 1085.36 / 16.779)$$

$$= 359.08 \ KJ . M^3 / Kg$$

$$b6 = - (Fo2S . Do2S) . (Hs - Hl) . k9 - Fo2S.XS(Hs - Hl)$$

$$= - 38.021 * (2801.5 - 1085.36) * (- 0.04946) - 2.04*.9(2801.5 - 1085.4)$$

$$= 70.41 \ KJ . M^3 / Kg . S$$

$$b8 = - (F1S . D1). Cp1$$

$$= - 380.21 * 5.518$$

$$= - 2097.84 \ KJ / S . k$$

b9 = D1 . Cp1 . (Ti1S - To1S)

= 5.518 * 1100 * (293.4 - 249)

= 269479.6 KJ / M^3

b10 = Di2 . H1

= 852.5 * 1085.36

= 925269.4 KJ / M^3

b11 = (F1S . D1). Cp1

= 380.21 8 * 5.518

= 2097.84 KJ . S / k

d4 = n . l . a . Cp1 / 2

= 1950 * 12.8 * 8.197E-05 * 5.518 * 1100

= 6208.82 KJ / k

k9 = - Di2 . Ds / ((Di2 - Ds) . Do2S)

= - 852.5 * 16.779 / ((852.5 - 16.779) * 18.602)

= - 0.04946 M^3/ Kg

k10 = a1 . b2 - b1 . a2

= 1327.79 * 359.08 - 1326996.02 * 6.357

= - 7957737.5 KJ / M^2

A(1,2) = - b6 . a2 / (2.0 . k10)

= - 70.41 * 6.356 / (2.0 * (- 7957737.5))

= 1.2015E-04 M^4/ Kg . S

A(1,4) = - b8 . a2 / (2.0 . k10)

= - 2097.8 * 6.356 / (2.0 * (- 7957737.5))

= - 8.378E-04 M / S . k

$A(2,2) = b6 \;.\; a1 \;/\; (2.0 \;.\; k10\ 0$

$= 70.41 * 1327.8 \;/\; \{ 2.0\ (-\ 79957737.5\ ) \}$

$= -\ 0.346 \;/S$

$A(2,4) = b8 \;.\; a1 \;/\; (2.0 \;.\; k10)$

$= 2097.8 * 1327.8 \;/\; \{ 2.0\ (-\ 79957737.5\ ) \}$

$= -\ 0.175\ \ M \;/\; S\ \ k$

$A\ (4,2) = b6 \;/\; (2.0\ .d4)$

$= 70.41 \;/\; (2.0 * 6208.8)$

$= 0.567E\text{-}02\ \ M^3 / Kg\ .\ S$

$A(4,4) = b8 \;/\; (2.0\ .\ d4)$

$= -\ 2097.8 \;/\; (2.0 * 6208.8)$

$= -0.169 \;/S$

$B(1,1) = -\ b9\ .\ a2 \;/\; (2.0\ .\ k10)$

$= -\ 269479.6 * 6.356 \;/\; \{ 2.0\ (-\ 7957737.5\ ) \}$

$= 0.108 \;/M^2$

$B(1,2) = (a10\ .\ b2 - b10\ .\ a2 \;/\; 2.0) \;/\; k10$

$= (852.5 * 359.08 - 925269.4 * 6.356 \;/\; 2.0) \;/\; (-\ 7957737.5)$

$= 0.331 \;/M^2$

$B(2,1) = b9\ .\ a1 \;/\; (2.0\ .\ k10)$

$= 269479.6 * 1327.8 \;/\; \{ 2.0\ (-\ 7957737.5\ ) \}$

$= -\ 22.48\ \ Kg \;/\; M^6$

$B(2,2) = (b10\ .\ a1 \;/\; 2.0 - a10\ .\ b1) \;/\; k10$

$= (925269.4 * 1327.8 \;/\; 2 - 852.5 * 1326996.01) \;/\; (-7957737.5)$

$= 64.883\ Kg \;/\; M^6$

$B(4,1) = b9 \;/\; (2.0\ .\ d4)$

$= 269479.6 \;/\; (2.0 * 6208.8)$

$= 21.7\ \ \ k \;/\; M^3$

$B(4,2) = b10 / (2.0 . d4)$

$= 925269.4 / (2.0 * 6208.8)$

$= 74.512 \ k / M^3$

$D(1,1) = - b11 . a2 / (2.0 . k10)$

$= - 2097.8 * 6.356 / (2.0 (- 7957737.5)$

$= 8.378E-04 \ M / S \ k$

$D(2,1) = b11 . a1 / (2.0 . k10)$

$= 2097.8 * 1327.8 / (2.0 (- 7957737.5))$

$= -0.175 \ Kg / M^3 . S . k$

$D(4,1) = b11 / d4 - 1.414 / t$

$= 2097.8 / (2.0 * 6208.8) - 1.414 / t$

$= (0.169 - 1.414 / t) = - 1.245 /S$ (since $t=1.0$)

b) CALCULATION OF c9 (ref. 13 Pp 254)

$$\text{Reynold's no } N_{re} = \frac{V . id . D1}{(mu)} = \frac{id . (F1S . D1)}{(mu) . n^2 \ a^2}$$

$$= \frac{0.0102 * 380.21}{10E-05 * 1950 * 8.197E-05}$$

$$= 2.43E+06$$

At this N_{re} friction factor , f = 0.007 (ref. 22 Pp 254)

thus using this value of f we get ,

$c9 = f . l . (F1S . D1) / (id . n . a)$

$= 0.007 * 12.8 * 380.21 / (.0102 * 1950 * 8.197)$

$= 130519.8 \ Kg / S . M^4$

TABLE - A.T1

LIST OF THE VARIABLES AND THEIR STEADY STATE VALUES

1.	hS - height of the liquid level in SG	:	6.4 M
2.	Do2S - density of outgoing steam	:	18.602 Kg / M^3
3.	PS - pressure drop in primary coolant tubes	:	13E+05 N / M^2
4.	To1S - outlet temperature of primary coolant	:	522 k
5.	F1S.D1 - mass flow rate of primary coolant	:	380.21 Kg / S
6.	Fo2S.Do2S - mass flow rate of secondary water	:	38.021 Kg / S
7.	XS - steam quality	:	0.9

TABLE - A.T2

LIST OF THE PARAMETERS AND THEIR VALUES

1.	D1 - average density of water	:	1100 Kg / M^3
2.	Ds - density of saturated steam at 521 k	:	16.779 Kg / M^3
3.	Di2 - density of saturated water at 521 k	:	852.5 Kg / M^3
4.	Ti1 - inlet temperature of primary coolant	:	566.4 k
5.	TB - temperature of the feed water	:	521 k
6.	Hl - enthalpy of saturated water at 521 k	:	1085.36 KJ / Kg
7.	Hs - enthalpy of saturated steam at 521 k	:	2801.5 KJ / Kg
8.	Cp1 - average specific heat of heavy water	:	5.518 KJ/Kg/ k
9.	mu - viscosity of heavy water at 523 k	:	1.0E-5 Kg/M/S
10.	a - cross sectinal area of a coolant tube	:	8.197E-5 M^2
11.	A - cross sectional area of the upper section of the steam generator	:	3.973 M^2
12.	A - cross sectional area of the lower section of the steam generator (excluding tubes)	:	1.644 M
13.	n - no of tubes per one steam grnerator	:	1950
14.	l - length of the U-tubes	:	12.8 M
15.	id - internal diameter of a single U-tube	:	1.02E-2 M
16.	L - shell height	:	8.0 M